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SUMMARY

The purpose of this report is to provide a description of the overall thrust, past relevant accomplishments and future work for research that was performed on the titled project. The purpose of this work was to perform applied research at the NASA Lewis Research Center in the area of the aeroelastic behavior of turbomachinery used in air-breathing propulsion. This activity was undertaken in close cooperation with the Structural Dynamics Branch of the Structures Division at NASA Lewis.

INTRODUCTION

Blade vibration phenomena such as flutter and forced response are important safety and reliability considerations in the design of turbines, fans and compressors. Blade fatigue induced by forced response of fan, compressor and turbine blades has caused serious engine failures. Meanwhile, reduced weight/size requirements and improved cycle efficiencies are leading to designs with higher risk associated with flutter and forced response.

The activities to be described were aimed at developing analytical methods to understand the above phenomena, efficient computational models to accurately and efficiently predict them, validation of these models using experimental and test data and dissemination of the developed methods and models to the industry.

PERSONNEL

This project was directed by Dr. Theo G. Keith, the Principal Investigator. The bulk of the research work was carried out by Dr. Durbha V. Murthy, a Senior Research Associate in the Mechanical, Industrial and Manufacturing Engineering Department at the University of Toledo. Close collaborators included George Stefko, and Tony Kurkov of NASA Lewis Research Center, and industrial collaborators from Allied-Signal, Pratt & Whitney and General Electric Aircraft Engines.

THE FREPS SYSTEM

The focus for much of the work carried out is the Forced Response Prediction System (FREPS) currently under development at NASA Lewis Research Center. This program is motivated by the paramount importance of accurately predicting theaeroelastic behavior of new generation air-breathing propulsion turbomachinery systems. The FREPS program is aimed at providing this capability in an analytical/computational tool that does not need excessive computational resources and is thus suitable for design environment. The objective of the FREPS system is to automatically and efficiently integrate blade structural dynamic, steady and unsteady aerodynamic analyses to calculate the forced vibration response amplitudes in turbomachinery blades to a variety of excitations. FREPS system can reduce the subjective element in the blade design process and improve the development cycle time for turbomachinery.

The basic objective in developing the FREPS system is to provide a state of the art quantitative forced response prediction tool that enables turbomachinery designers to improve the fatigue characteristics of the blades in a systematic manner. We expect that FREPS will lead to less stringent safety factors and margins and shorter development and testing periods and turbomachinery with higher performance. The distinctive characteristics of FREPS are: 1) it integrates advanced numerical procedures from the two disciplines of structures and aerodynamics and 2) it is computationally efficient. The actual flow path geometry and material properties can be used because of the availability of advanced structural and aerodynamic models which account for the effects of thickness, camber and incidence. The calculation of the effects of the distortion of the exciting gust through the blade passage is an important capability. In addition, the computational efficiency of the FREPS system allows the examination of the forced vibratory characteristics for various design choices and the conduct of parametric studies that can be used to improve blade designs.

To advance the stated goal of quick technology transfer to industry, a workshop was conducted at NASA Lewis on Forced Response in Turbomachinery on August 11, 1993. The principal investigator, Durbha V. Murthy, played a major role in organizing and conducting the workshop. It provided a forum to transfer technology to industry and to obtain industry and university input for future work. About 35 people attended representing 6 rocket and aircraft engine industries and 6 universities. Eight presentations were made describing the results of NASA funded research in the areas of aeroelastic response prediction, steady and unsteady fluid dynamics, mistuning, and associated experiments. Two of the presentations were made by the principal investigator. This work will lead to increased engine reliability and lower engine fuel consumption. The attendees participated in lively question and answer sessions at the end of each presentation. An open discussion session at the end of the workshop was devoted to the evaluation of the work by industry participants and suggestions for further work that would be of large benefit to engine industry. The workshop ended with a demonstration of the Forced Response Prediction System (FREPS) code, developed partially under this grant. In addition to fulfilling the technology transfer objectives of NASA, this workshop provided an opportunity for industry representatives to make recommendations for future NASA research work in this important technology area.

To demonstrate the capabilities and computational efficiency of the FREPS system, the effect of blade thickness on the aeroelastic forced response of turbomachinery rotors was investigated. This study was motivated by a question that was recently posed on whether a thicker blade necessarily has a reduced vibratory response. Test rotors with different blade thicknesses were analyzed. It was demonstrated that, for some nodal diameter modes, aerodynamic damping reduced with increased blade thickness and could possibly lead to higher dynamic stress amplitudes in thicker blades, counter to intuition. For the cases examined where thicker blades experienced higher stresses, an analysis of the aerodynamic damping and excitation forces showed that the higher stresses were a result of higher aerodynamic excitation and that the effect of reduced aerodynamic damping is small. Results of this investigation were documented in a paper (Murthy, Hoyniak and Morel, 1994).

A definite consensus has emerged at the Workshop that FREPS will be relatively less useful to the industry if it needs a Cray-YMP computer to run. A workstation-class computer is preferred by the industry. The system has recently been ported to a workstation and enhanced with graphical postprocessing. This will also allow a more friendly interface to be implemented. propulsion systems. The code was demonstrated to key aeromechanics engineers and managers in the U.S. engine industry at a 1993 workshop. The aerodynamic modules of the FREPS system have been successfully compared to test results from General Electric.

One of the primary goals of this work has been to quickly transfer the technology developed to private industry. Towards this end, a substantial portion of the efforts relevant to this proposal is directed to establishing a close working relationship and rapport with personnel from private industry who are trying to solve practical problems in the area of aeroelasticity of turbomachinery. As part of the Space Act Agreement between NASA Lewis Research Center and the General Electric Aircraft Engines Company, the FREPS code was successfully installed at GEAE. In order to facilitate this, the proprietary steady aerodynamic code that was being used in FREPS was replaced by a public-domain steady aerodynamic code called SFLOW developed by Dan Hoyniak of NASA Lewis Research Center. The FREPS code installed at GEAE will be used for cooperative research projects between NASA Lewis Research Center and the General Electric Aircraft Engines Company. It is expected that the FREPS system will contribute substantially to future design efforts of this company. In addition, a draft of a User's Manual for the code is ready and is going to be published soon. A shorter version of the User's Manual, which describes the use and capabilities of the FREPS system has been published and presented (Murthy and Morel, 1993).

Another aspect of forced response of turbomachinery in space propulsion is the influence of small, unavoidable blade-to-blade variations in rotors, known as mistuning. Potentially damaging dynamic behavior of mistuned systems has attracted great attention in the recent past, even though most of the work has neglected the effect of unsteady aerodynamic forces. Some efforts by personnel associated with this proposal have demonstrated some of the consequences of the presence of mistuning in single rotor systems, including the effect of unsteady aerodynamic forces. Pierre and Murthy (1991) demonstrated for the first time the drastic changes in aeroelastic characteristics of single rotor systems, such as the loss of aeroelastic eigenstructure and the localization of aeroelastic mode shapes. Localization of aeroelastic mode shapes results in only a few blades absorbing all the energy of external excitation and suffering much more fatigue compared to the predictions by conventional methods that usually ignore mistuning. It was shown that these phenomena could occur for even small values of random mistuning, of the order that is normally present in realistic rotors. A perturbation method, that yielded insight into the qualitative behavior of mistuned aeroelastic systems, was developed. The perturbation method also provides a quick procedure to check if large changes can be expected by considering a given level of mistuning.

Mode Localization in SSME HPOTP Turbine

To demonstrate the mode localization phenomena in an existing engine structure, the High Pressure Oxygen Turbo Pump (HPOTP) turbine of the Space Shuttle Main Engine (SSME), which had the structural and aerodynamic characteristics typical of the new generation high-energy turbines for space propulsion, was studied by Pierre, Smith and Murthy (1991). The aeroelastic behavior of the HPOTP turbine blades was obtained using a finite element structural model and an advanced aerodynamic model that accounts for the effects of camber, incidence and thickness. The extreme sensitivity to mistuning and the occurrence of localized vibrations were demonstrated for this class of turbines. A second major contribution has been the preliminary investigation into a powerful sensitivity measure that could allow the global prediction of mistuning effects based solely on the knowledge of the tuned or the nominal system behavior. This sensitivity measure had the potential to help avoid engines that are pathologically sensitive to mistuning and was particularly suited for the design environment. Further work regarding the practical utilization of the demonstrated potential of this sensitivity measure was documented by Murthy and Pierre (1992) and is described in the next paragraph.

Mistuning Sensitivity Measure and Application to Optimal Design

While the phenomenon of mode localizaton can be extremely dangerous when it occurs, most analysis and design procedures routinely ignore mistuning in practice. Though this could earlier have been attributed to the lack of pertinent information on the mode localization phenomenon, mistuning is ignored in present design and analysis procedures mainly because (a) tremendous computational and analytical complexities are involved in dropping the assumption of tuned rotors (that is, those having identical blades) and more importantly, (b) the actual mistuning pattern and its standard deviation are generally not available until the design and manufacture of the rotor is complete. Although the tuned rotor assumption is extremely useful for the analysis of complex rotor systems such as high-performance turbomachinery, mistuned rotors may exhibit dynamic characteristics that are vastly different from those of tuned rotors due to phenomena such as mode localization. Murthy and Pierre (1992) and Murthy, Pierre and Ottarsson (1992) addressed the need for an easy-toimplement procedure to account for the effects of mistuning in the current analysis and design procedures.

A stochastic measure of sensitivity was developed by Murthy and Pierre (1992) in order to predict the effects of small random blade mistuning on the dynamic aeroelastic response of turbomachinery blade assemblies. This sensitivity measure is based solely on the nominal system design (i.e., on tuned system information), which makes it extremely easy and inexpensive to calculate. Though structural coupling was not accounted for, the measure could become a valuable design tool that will enable designers to evaluate mistuning effects at a preliminary design stage. The predictive capability of the sensitivity measure is illustrated by examining the effects of mistuning on the aeroelastic modes of the first stage of the oxidizer turbopump in the Space Shuttle Main Engine. Results from a full analysis of mistuned systems confirm that the simple stochastic sensitivity measure predicts consistently the drastic changes due to mistuning and the localization of aeroelastic vibration to a few blades.

Murthy, Pierre and Ottarsson (1992) presented a strategy to develop a constraint based on a similar approach that can be used for optimal design of an engine rotor. The approach accounted for structural coupling (but not aerodynamic coupling) and was illutsrated by applying it to a model popularly used to analyze bladed-disk vibrations. The proposed constraint is again dependent on the properties of only the tuned system, so a mistuned system analysis is not needed. The principal difficulty in modeling mistuning was overcome by employing a statistical model, which does not require knowledge of the actual mistuning pattern. This is practical because the statistics of expected mistuning may be more readily obtained or estimated than the actual mistuning pattern. The complex and time-consuming task of a mistuned system analysis is avoided by employing perturbation theory in deriving the constraint. As a result, the proposed constraint is very inexpensive to compute. This constraint is also easy to differentiate, sensitivity analysis of the constraint imposes no additional burden, provided a sensitivity analysis of the tuned assembly is already available. Thus, it is suitable for the computation-intensive applications of optimization of engine rotors.

Further work on mistuning in the context of design optimization has been initiated in cooperation with Brian Watson, a doctoral student and Professor Manohar Kamat of the Georgia Institute of Technology. Unlike previous attempts in mistuning optimization, which considered mistuning as a design parameter and thus failed to be of practical utility, in this work, mistuned blades are considered to be given and the pattern of arrangement of blades around the rotor is optimized for the least response to excitation at a given frequency. This is a more practical approach than earlier attempts at mistuning optimization because, in practice, mistuning arises out of manufacturing tolerances and is thus usually out of the designer's control. Work on this problem was guided by the principal investigator serving on the dissertation committee of Brian Watson. The study was documented in the dissertation and a series of papers derived therefrom. (*E.g.*, Watson, Kamat and Murthy, 1993).

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